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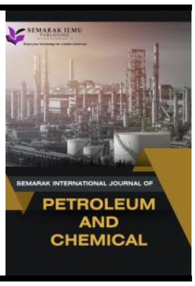

From Waste to Wealth: Circular Economy Breakthroughs in Fuels and Chemicals

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ABSTRACT

This article explores the transformative potential of the circular economy in the fuels and chemicals sectors, emphasizing the urgent need to move beyond the traditional linear “take-make-dispose” model to one that designs out waste, keeps materials in use, and regenerates natural systems. Against the backdrop of rising global greenhouse gas emissions and resource depletion, the article highlights how circular strategies-supported by legislative action and industry innovation-can reduce emissions by up to 39% and unlock significant economic value. Key breakthroughs discussed include advanced chemical recycling (such as pyrolysis and solvolysis) that convert hard-to-recycle plastics into new feedstocks, biological conversions that turn agricultural and organic waste into biofuels and chemicals, and carbon capture and utilization technologies that transform industrial emissions into valuable products. The article also examines the scaling of waste-derived biofuels from used oils and fats, and the emergence of digital tools that optimize circular systems. Through global and Southeast Asian case studies, the article demonstrates how these innovations are blurring the line between waste management and resource production, driving both environmental sustainability and economic growth. It concludes with strategic recommendations for academia and industry to accelerate the adoption of circular economy practices, positioning waste as a valuable resource in the transition to a more sustainable future.

1. Introduction

The transition “from waste to wealth” through circular economy breakthroughs in fuels and chemicals represents a topic of urgent global importance. Currently, 45% of global greenhouse gas (GHG) emissions are attributed to the production and manufacturing of materials and products, making the traditional linear model of “take-make-dispose” no longer viable and necessitating its rethinking [1]. The concept of a circular economy (CE) offers a transformative paradigm in which waste is designed out, materials are kept in use, and natural systems are regenerated. This paradigm is especially critical for the chemical and fuel sectors, which have historically depended on virgin fossil resources and have been associated with significant emissions. These sectors provide the building

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blocks for countless products and all forms of energy carriers; therefore, advancing circular practices in chemicals and fuels can have a powerful multiplier effect across the entire economy. Consequently, the provision of circular materials and sustainable fuels is increasingly becoming a requirement to remain competitive and to meet climate goals in the 21st century.

Globally, momentum toward circular economy strategies is growing among policymakers, companies, and researchers as a response to mounting environmental challenges such as plastic pollution, resource depletion, and climate change. Legislative support has been enacted in multiple jurisdictions, including the EU's Circular Economy Action Plan and China's circular economy promotions, signaling broad recognition of the need to reduce resource use and waste. These measures have the potential to reduce global GHG emissions by nearly 39% through more circular approaches [1]. Concurrently, leading firms in the chemical industry have initiated pilot projects involving disruptive innovations aimed at driving circularity, such as the conversion of post-consumer waste into new feedstocks, as part of their net-zero and sustainability roadmaps. Similar shifts are being observed in the fuels sector, with developments including biofuels derived from agricultural residues, renewable diesel from waste oils, and jet fuel produced from captured carbon emissions. All these efforts are guided by the central principle of the circular economy: waste is not regarded as an endpoint but as a resource to be cycled back into production.

The importance of circular economy approaches for chemicals and fuels is underscored by their potential to deliver not only significant environmental benefits, such as lower emissions and reduced pollution, but also substantial economic opportunities. Estimates suggest that transitioning to a circular economy could generate up to $4.5 trillion in additional economic output by 2030 through new business models, increased efficiencies, and expanded markets [3]. This dual promise of sustainability and economic growth is particularly appealing to both emerging economies and established industries shown in Figure 1. For the chemical and fuel sectors, which are often characterized by high capital investments and complex supply chains, the circular economy opens pathways for innovation, including the design of recyclable products, the use of alternative feedstocks, and the development of new processes that convert waste into valuable resources.

Fig. 1. Linear vs. circular economy (39% less GHG)

Major breakthroughs and trends enabling this transformation have been identified, particularly in the conversion of diverse waste streams into value-added fuels and chemicals at scales previously considered infeasible. Critical technological enablers include novel recycling methods, bioconversion techniques, and digital tools that streamline circular systems. Regionally, Southeast Asia exemplifies a landscape rich in both challenges and innovative circular economy initiatives [2]. Key efforts and case studies from this region such as plastic recycling in Malaysia, biomass valorization in Thailand, and biofuel production from palm waste in Indonesia and Malaysia highlight the sustainability and economic gains achievable through circularity. Strategic recommendations have been formulated to accelerate the adoption of circular economy practices within academia and industry, aiming to further drive this agenda.

2. Waste-to-Wealth: Breakthroughs and Trends in Converting Waste to Fuels and Chemicals

Over the past decade, significant advancements have been made in “waste-to-x” technologies, encompassing a broad range of methods aimed at converting various waste streams into fuels, chemicals, or materials. These technological developments have become central to the practical implementation of the circular economy by enabling the reutilization of waste as feedstocks for industrial processes.

One major area of progress involves advanced plastic-to-fuel and chemical conversion technologies. Traditional mechanical recycling methods are limited to processing certain types of clean, single-polymer plastics, whereas multi-layer packaging, contaminated plastics, and composite materials frequently end up in landfills or the environment. Chemical recycling methods, such as pyrolysis and gasification, have been developed and scaled to decompose mixed plastic waste into basic hydrocarbon products. Pyrolysis, for example, converts low-quality and hard-to-recycle plastics into pyrolysis oil, a crude oil-like substance that can serve as feedstock for new plastic or fuel production, effectively closing the material loop. A notable industrial example is the commissioning of a pyrolysis oil upgrading facility by Shell in Singapore, with a capacity of 50,000 tons per year, designed to process hard-to-recycle plastic waste into chemical feedstock for petrochemical production [6,7]. Similar initiatives are underway in Europe and North America, where startups and collaborations are producing fuel oils, monomers, and specialty chemicals from waste plastics through advanced recycling technologies. These developments contribute to reducing dependence on virgin fossil resources and mitigating plastic pollution.

Biological and biomass conversion technologies represent another significant domain of innovation. The use of microbial, enzymatic, and fermentation processes has enabled the conversion of agricultural residues, food waste, and industrial emissions into fuels and chemicals. Cellulosic biorefineries are advancing toward commercial scale, converting biomass such as corn stover, rice straw, and sugarcane bagasse into ethanol and other biofuels. An illustrative case is the enzyme-assisted conversion of sugarcane bagasse in Thailand, demonstrated through a collaborative project with Japan’s New Energy and Industrial Technology Development Organization (NEDO) [11]. This process integrates cellulose hydrolysis and fermentation into a single step, reducing production costs and providing a replicable model for bioethanol production in sugar-producing regions. Additionally, anaerobic digestion of organic waste to produce biogas is a well-established technology that continues to be optimized and scaled, contributing renewable natural gas for power generation and transportation.

Carbon capture and utilization (CCU) technologies have also emerged as promising approaches for converting industrial waste gases and CO_2 emissions into valuable products. For instance, LanzaTech has developed a microbial fermentation process that utilizes carbon-rich waste gases from steel production, converting them into ethanol [12,20]. This ethanol can subsequently be upgraded into chemicals or drop-in fuels. A notable demonstration involved the production of jet fuel from steel mill emissions, which powered a commercial flight in 2018. More broadly, CCU technologies employing renewable energy sources are being developed to convert captured CO_2 into fuels and chemicals, including electrochemical reduction to methanol and algae-based biomass production. These approaches highlight the potential for integrating flue gases and CO_2 into circular carbon economies.

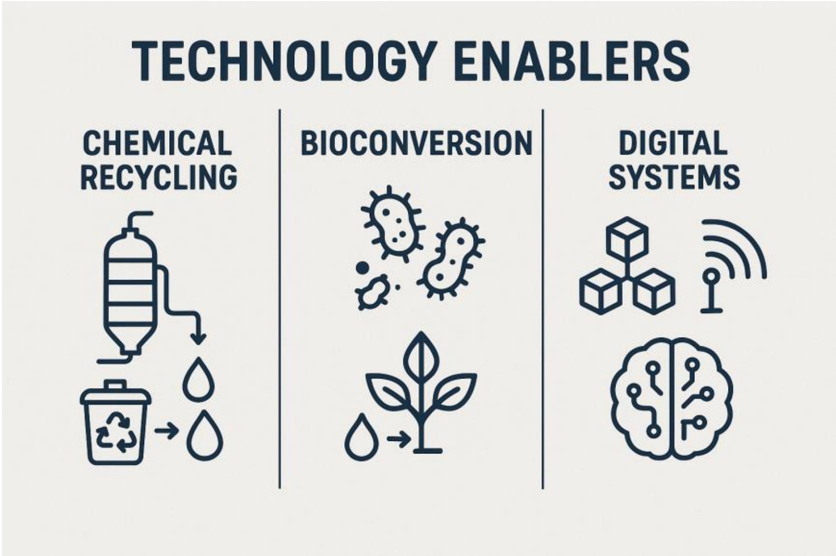
In the fuels sector, the conversion of waste oils and fats into renewable biodiesel and sustainable aviation fuels (SAF) has gained traction [13]. Waste streams such as used cooking oil, grease, and animal fats are collected and processed via transesterification or hydrotreating to produce biodiesel and SAF. These second-generation biofuels utilize waste residues rather than food crops, addressing both waste management and fuel production objectives. Several countries have implemented blending mandates to encourage the use of waste-derived fuels. For example, Indonesia's biodiesel program incorporates used cooking oil and palm fatty acid distillates within its B30 blend mandate, and commercial airlines have conducted test flights using SAF derived from waste fats and oils.

Additional developments include advances in chemical catalysis, where novel catalysts enable the upcycling of plastic waste into higher-value specialty chemicals, such as lubricant oils and waxes. Thermochemical processes like hydrothermal liquefaction have also been applied to convert wet wastes, including sewage sludge and algae, into crude-like bio-oils. Collectively, these innovations demonstrate that materials previously considered non-recyclable or low-value—such as mixed plastics, lignocellulosic biomass, and industrial gases—are increasingly being utilized as viable feedstocks for fuels and chemicals production. This convergence of technologies is reshaping the boundaries between waste management and resource production, thereby supporting the circular economy framework.

Following this overview of global technological advancements in waste conversion, subsequent discussion will focus on the enabling technologies and digital tools that facilitate the integration and optimization of circular systems, encompassing chemical, biological, and computational innovations.

3. Technology Enablers: Chemical Recycling, Bioconversion, and Digital Tools

The practical realization of a circular economy in the fuels and chemicals sectors is contingent upon the deployment of appropriate technologies at scale. Three principal categories of technology are identified as critical enablers: advanced recycling processes (chemical recycling), bioconversion and bio-based technologies, and digital tools and data-driven systems, as illustrated in Figure 2.



(a) (b) (c)

Fig. 2. Technology enablers. (a) Chemical recycling (b) Bioconversion (c) Digital systems

3.1 Chemical Recycling Technologies

Traditional mechanical recycling involves the physical reprocessing of materials, such as melting plastics; however, it is constrained by material quality degradation and contamination. Chemical recycling, by contrast, encompasses technologies that chemically transform waste polymers into useful raw materials, effectively resetting the material to its fundamental building blocks. Several forms of chemical recycling are currently in use or development:

3.1.1 Pyrolysis

Pyrolysis involves heating mixed plastic waste in the absence of oxygen, breaking long polymer chains into shorter hydrocarbons (pyrolysis oil). This oil can be refined and used as a substitute for fossil feedstock in petrochemical plants. Pyrolysis is capable of processing mixed and low-quality plastics, including multi-layer packaging and contaminated films. The technology has advanced rapidly; for example, a partnership between PETRONAS Chemicals Group and Plastic Energy in Malaysia is constructing a 33,000 tonne-per-year plant utilizing patented pyrolysis technology to convert end-of-life plastics into TACOIL™ feedstock for new plastics, supporting Malaysia's circular plastics roadmap [16]. Such plants enable plastics-to-plastics recycling at the molecular level.

3.1.2 Solvolysis (chemical solvent recycling)

Solvolysis employs solvents to dissolve polymers, enabling the precipitation or separation of the polymer or its monomers. Examples include glycolysis of PET to monomers or the depolymerization of nylon via solvents. These processes can yield virgin-quality monomers from waste polymers, which can subsequently be re-polymerized. Chemical companies have developed solvolysis-based recycling for polyesters and polyurethanes, complementing pyrolysis.

3.1.3 Gasification and synthesis

Gasification converts organic wastes, including plastics or biomass, at high temperature with limited oxygen into syngas (a mixture of carbon monoxide and hydrogen). Syngas can then be catalytically converted into fuels or chemicals via processes such as Fischer-Tropsch synthesis or methanol synthesis. Several pilot plants are exploring the gasification of municipal solid waste to produce ethanol or diesel.

3.1.4 Catalytic upcycling

This emerging area involves the direct catalytic transformation of polymers to higher-value products. For example, researchers have developed catalysts that break down polyethylene into synthetic waxes or oils in a controlled manner, or convert polyolefins into aromatic chemicals [19]. While not yet commercial, these innovations suggest the potential for upgrading plastics into more valuable chemical products, thereby increasing the economic incentive for waste recovery.

In summary, chemical recycling technologies expand the range of waste materials that can be recycled and are essential to achieving circularity in the chemical sector. These technologies enable the maintenance of carbon molecules in plastics and other materials within the value chain, rather than their disposal.

3.2 Bioconversion and Bio-Based Technologies

Bioconversion technologies leverage biological pathways to convert waste materials into useful products, often operating at lower temperatures and energy inputs due to the use of enzymes and microbial catalysts. Several technological avenues are noteworthy:

3.2.1 Anaerobic digestion and fermentation

Anaerobic digestion employs microbial communities to break down organic waste into biogas (a mixture of methane and carbon dioxide). Recent developments include engineered digesters capable of handling mixed solid waste or specific feedstocks more efficiently, and the upgrading of biogas to biomethane for grid injection or vehicle fuel. Fermentation technologies can convert waste sugars or gases to products. For example, LanzaTech's gas fermentation uses specialized microbes to ferment industrial off-gases (rich in carbon monoxide or carbon dioxide) into ethanol and chemicals [20]. This integration of biotechnology and chemical catalysis provides a template for converting waste carbon emissions into drop-in fuels.

3.2.2 Enzymatic and microbial processing of biomass

Advanced enzyme technologies facilitate the breakdown of lignocellulosic biomass, such as agricultural residues and wood waste, into fermentable components. Improvements in enzyme efficiency and production have reduced costs. For instance, the Thai bagasse-to-ethanol project utilized a custom enzyme cocktail to saccharify bagasse, converting cellulose to sugar and subsequently fermenting it to ethanol in a single step, thereby demonstrating cost-effective lignocellulose conversion. Engineered microbes are also being developed to convert waste feedstocks into high-value chemicals.

3.2.3 Bio-catalytic upcycling

This concept involves the use of microbes to upcycle wastes into novel products. Certain bacteria can metabolize plastic waste, such as PET, and excrete precursor chemicals for new polymers. Although in early stages, these approaches may complement chemical methods for processing materials that are challenging to recycle chemically.

3.2.4 Biorefineries and co-products

The biorefinery concept is being extended to utilize every fraction of biomass. For example, palm oil mills or sugar mills can operate biorefineries that produce energy, fuels, and chemicals from residues. In Malaysia and Indonesia, research is ongoing regarding palm oil mill effluent (POME), a wastewater with high organic content, converting it into biogas energy or liquid fuels. A recent study demonstrated the conversion of POME into bio-jet fuel by combining enzymatic hydrolysis and catalytic upgrading, achieving a high yield of green kerosene suitable for sustainable aviation fuel [17]. These technological advances indicate that even wastewater from food crop processing can be transformed into high-value, clean fuels, aligning with circular economy principles.

3.3 Digital Tools and Data-Driven Systems

Digital innovation is increasingly recognized as a critical enabler of the circular economy [14]. A circular system requires coordination across value chains, transparency of material flows, and optimization of complex processes, all of which are facilitated by digital tools:

3.3.1 Material traceability and blockchain

Blockchain technology provides transparent, tamper-proof tracking of materials from source through recycling processes. For example, Plastic Bank uses blockchain to track and reward recycling activities, creating a trusted record of recycled plastic credits. In the waste management sector, Suez has used blockchain to record the transfer and reuse of wastewater sludge in agriculture, ensuring documentation and transparency at all stages [14].

3.3.2 IoT and smart waste collection

The Internet of Things (IoT) utilizes sensors and connected devices to modernize waste logistics [14]. Smart sensors in bins can signal when recycling containers are full, optimizing collection routes and reducing operational costs and emissions. In industrial settings, IoT sensors monitor waste generation in real time, allowing for process adjustments to minimize waste.

3.3.3 Artificial intelligence and process optimization

Artificial intelligence and data analytics are applied to improve recycling processes and conversion technologies. AI-powered robots and optical sorters at recycling facilities can identify and separate materials with greater accuracy and speed than manual sorting. In chemical recycling plants, AI models and digital twins can optimize reactor conditions for maximum yield and energy efficiency.

3.3.4 Platforms and marketplace

Digital platforms connect waste generators with potential users, creating marketplaces for secondary materials. These platforms reduce transaction costs and help achieve industrial symbiosis at scale by making smaller waste streams accessible for valorization.

3.3.5 Analytics for circular design

Big data analytics inform product design for circularity by identifying waste generation points and feeding this information back to research and development teams. This supports the redesign of products for easier recyclability and compatibility with circular processes.

In summary, digital tools function as the "nervous system" of the circular economy, enabling the monitoring, coordination, and optimization of resource flows. When integrated with physical recycling and bioconversion technologies, digital innovations amplify the impact and efficiency of circular solutions.

4. Southeast Asia's Circular Economy Journey: Initiatives, Challenges, and Success Stories

Southeast Asia (SEA) comprises diverse countries at varying stages of economic development, presenting a complex context for the implementation of circular economy principles. The region is characterized by rapidly growing populations and economies, which have contributed to increased consumption and waste generation. Consequently, SEA countries are disproportionately represented among the global contributors to marine plastic pollution, with six of the top ten contributors to ocean plastic waste being members of the Association of Southeast Asian Nations (ASEAN) [4]. Landfilling remains the predominant waste disposal method, and open dumping or burning of waste persists in certain areas. These conditions highlight both the challenges and the potential for circular economy adoption within the region.

4.1 Policy Initiatives and Regulatory Frameworks

Governments and industries across Southeast Asia have initiated various circular economy strategies in recent years. Several countries have integrated circular economy objectives into national development plans. Thailand, for example, has adopted the "Bio-Circular-Green (BCG) Economy" model, emphasizing sustainable biological resource use, circular waste management, and green growth. This includes support for bioenergy, bioplastics, and recycling sectors. Vietnam approved a National Action Plan on circular economy in 2022, establishing targets for waste reduction, recycling rates, and renewable resource utilization [21]. Indonesia has incorporated circular economy goals into its economic framework and is developing regulations to limit single-use plastics and promote waste-to-energy projects. Malaysia has launched a Circular Economy Roadmap for Plastics (2021–2030) aimed at phasing out problematic plastics and expanding recycling infrastructure, supported by investments such as PETRONAS's advanced recycling project.

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Waste-to-energy and renewable fuel policies have also been advanced. Singapore has employed waste-to-energy incineration with energy recovery to reduce landfill dependence and is exploring chemical recycling technologies for plastics. Indonesia has issued regulations to develop waste-to-energy incineration facilities in urban centers, although progress has been variable. Malaysia and Thailand provide incentives and feed-in tariffs to encourage biomass power projects utilizing agricultural residues such as rice husks and palm shells. Sustainable Aviation Fuel (SAF) has gained policy attention; Thailand is considering a target of 1% SAF usage by 2026, and Malaysia's 2024 budget includes provisions for SAF production from palm oil waste, supported by the national oil company.

Regional cooperation has been promoted through platforms such as the ASEAN Secretariat, with partners including the European Union and Japan. These collaborations focus on harmonizing standards, facilitating recyclable material trade, knowledge transfer, pilot projects, and financing mechanisms to scale circular economy solutions in Southeast Asia [15].

4.2 Challenges to Circular Economy Implementation

Despite growing momentum, several challenges impede the widespread adoption of circular economy practices in Southeast Asia. Waste management infrastructure remains insufficient in many areas, particularly in rural and peri-urban regions where informal systems predominate. Landfills and unmanaged dumpsites are common disposal methods, complicating the sourcing of clean and segregated waste streams necessary for advanced recycling and bioconversion technologies. Significant investment is required to expand waste collection, sorting, and preprocessing facilities.

The informal waste sector plays a substantial role in material recovery, with estimates indicating that over 90% of recyclable plastics in Vietnam are processed by informal workers [21]. Integrating or formalizing this sector without disrupting livelihoods presents a policy challenge. Approaches such as organizing waste picker cooperatives and partnerships between industry and local aggregators have been employed to maintain the inclusion of informal workers within recycling value chains.

Financing circular economy projects is constrained by high upfront costs and uncertain returns, particularly in developing markets. Market conditions, including low landfill costs and volatility in oil prices, affect the competitiveness of recycled products. Governments have begun to implement measures such as tax incentives, green funds, and public-private partnerships to mitigate investment risks.

Technical expertise and supply chain logistics also pose challenges. Advanced technologies, such as chemical recycling and cellulosic ethanol production, require skilled operation and consistent feedstock supply. The aggregation and transport of biomass from numerous small-scale agricultural producers remain complex. Pilot projects have demonstrated technical feasibility, but scaling to commercial operations while maintaining feedstock quality is ongoing.

Policy enforcement and public participation vary across the region. Enforcement of plastic bans and recycling mandates is sometimes limited by resource constraints and governance issues. Public awareness and engagement in recycling programs are uneven, with consumer sorting practices generally underdeveloped. Nonetheless, civil society organizations and youth movements have contributed to raising awareness of plastic pollution and sustainability.

5. Case Studies: Circular Economy Applications in Southeast Asia

Several case studies illustrate the application of circular economy principles in Southeast Asia, including plastic waste recycling initiatives, biomass valorization projects, and palm oil waste-to-fuel programs. These examples demonstrate the potential for circular economy strategies tailored to the regional context.

5.1 Plastic Waste to Petrochemical Feedstock in Malaysia

Malaysia has implemented advanced chemical recycling to address plastic waste management. In October 2023, PETRONAS Chemicals Group (PCG) finalized the investment decision for Asia's largest advanced chemical recycling plant in Pengerang, Johor, with a processing capacity of 33,000 tonnes per year [16]. The facility utilizes Plastic Energy's patented pyrolysis technology to convert end-of-life mixed plastics into TACOIL™, a purified pyrolysis oil suitable as a petrochemical feedstock for new plastics and chemicals. This process allows partial substitution of fossil oil and supports the national Plastic Sustainability Roadmap 2021–2030, which aims to phase out single-use plastics and promote a circular plastics economy.

The integration of this facility into Malaysia's plastics value chain is expected to stimulate demand for post-consumer plastics and foster innovation across collection, processing, and manufacturing sectors. This initiative aligns with national waste reduction goals and the increasing demand for sustainable packaging among major brands. The project also exemplifies cross-sector collaboration, involving technology transfer from a European cleantech company, local engineering firms, and alignment with government policy. If successful, it may catalyze similar projects across the ASEAN region, contributing to reduced plastic leakage, lower lifecycle carbon emissions, and employment growth in recycling and processing operations. The plant is positioned to increase the recycling rate of plastics in Malaysia, which has historically been low, and to create a market for materials previously destined for landfill or the environment.

5.2 Agricultural Biomass Valorization: Bagasse to Bioethanol in Thailand

Thailand, as a major agricultural producer, generates substantial quantities of residues such as rice straw, cassava pulp, oil palm fronds, and sugarcane bagasse. Traditionally, these residues have been disposed of through open burning or low-value applications. In alignment with the Bio-Circular-Green (BCG) economy agenda, Thailand has pursued the valorization of agricultural waste into higher-value products.

A notable example is the production of cellulosic ethanol from sugarcane bagasse. A demonstration project at Thai Roong Ruang Energy Co. in Saraburi, established under Japan's Green Partnership Program, successfully produced bioethanol from bagasse using an enzyme-based process by 2017 [10]. The plant, recognized by Japan's NEDO as a model, integrates enzymatic hydrolysis and fermentation in a single step, thereby optimizing the conversion of cellulose to fermentable sugars and ethanol [11]. This approach reduces process complexity and cost, and is tailored for local feedstock characteristics.

The demonstration confirmed the technical and economic feasibility of producing fuel-grade ethanol from agricultural waste rather than food crops. If scaled, this technology could reduce open burning of residues, provide additional revenue streams for farmers and mills, and enhance domestic renewable fuel supply. The project also highlights the role of international collaboration and technology transfer in advancing circular economy solutions. The Thai government, local industry, and Japanese partners each contributed policy support, feedstock, technology, and investment. This model illustrates the potential for other Southeast Asian countries with abundant biomass resources to develop sustainable biofuels and chemicals, contingent on appropriate technology and policy support.

5.3 Palm Oil Industry Waste to Biofuels in Malaysia and Indonesia

The palm oil industry, a major economic sector in Malaysia and Indonesia, generates significant volumes of waste, including empty fruit bunches (EFB), palm kernel shells, fronds, and palm oil mill effluent (POME). While some residues are utilized for process energy, a substantial portion remains underutilized or causes environmental concerns.

Recent initiatives have focused on converting palm oil residues into value-added products, particularly biofuels [22]. Malaysia has announced plans to increase sustainable aviation fuel (SAF) production from palm oil waste, involving state-owned Petronas and palm plantation companies. The strategy targets the use of palm fatty acid distillate (PFAD), used cooking oil, and other residues as feedstocks for biojet fuel production. This aligns with international aviation industry efforts to adopt low-carbon fuels and leverages Malaysia’s abundant waste streams.

Technical research and pilot projects have demonstrated the conversion of POME into biojet fuel through enzymatic and catalytic processes, achieving notable selectivity to kerosene-range hydrocarbons. EFB has been processed into bioethanol, biochar, and syngas for power generation, while used palm cooking oil is collected for biodiesel production. These approaches provide higher-value applications for waste oils and solid residues, contributing to waste reduction and circularity in the palm oil sector.

Malaysia produces approximately 90 million tonnes of oil palm biomass annually, with only a fraction currently utilized. Government policy now identifies biomass as a strategic sector, with efforts aimed at maximizing the use of all palm byproducts. The conversion of POME and PFAD into biofuels is incentivized by international demand for waste-based biodiesel feedstocks. These initiatives are expected to reduce methane emissions, limit deforestation by avoiding additional land use, and create rural economic opportunities through new business models in bioenergy and biorefining. Collaboration among universities, industry, and government is central to advancing these technologies and integrating them into existing operations.

Table 1
Summary of Circular Economy Case Studies in Southeast Asia [10,11,16,22]

Case Study Location / Sector	Waste Feedstock	Technology Used	Product Output	Key Outcomes / Benefits
Malaysia– Plastics	Post-consumer plastic waste	Advanced chemical recycling (pyrolysis)	Pyrolysis oil as feedstock for new plastics and chemicals	Closes plastics loop; diverts 33,000 t/year of waste; supports national circular plastics roadmap; reduces fossil feedstock use; creates green jobs and stimulates value chain innovation.
Thailand–Sugar Industry	Sugarcane bagasse	Enzymatic hydrolysis & fermentation	Cellulosic ethanol	First operational cellulosic ethanol demonstration in SEA; avoids open burning of residues; creates rural revenue streams; supports BCG economy agenda; demonstrates international technology transfer.
Malaysia/Indonesia–Palm Oil Sector	Palm oil mill effluent (POME), empty fruit bunches (EFB), palm fatty acid distillate (PFAD), used palm cooking oil	Biochemical & catalytic conversion (e.g., enzymatic hydrolysis, catalytic upgrading, biogas, biodiesel production)	Biofuels (biodiesel, sustainable aviation fuel, biogas, bioethanol, biojet fuel)	Reduces waste pollution and methane emissions; produces renewable fuels; supports SAF and biodiesel targets; creates rural jobs; utilizes >90 Mt/yr palm biomass; avoids landfilling and open burning.

These case studies, summarized in Table 1, demonstrate the application of circular economy principles to major regional waste streams. Each example illustrates the conversion of waste into economically valuable products, the role of technology and policy, and the importance of cross-sector collaboration in overcoming operational and market challenges.

6. Sustainability Impacts, Economic Benefits, and the Role of Collaboration in Circular Economy Initiatives

6.1 Environmental Sustainability

Circular economy initiatives in Southeast Asia have demonstrable impacts on environmental sustainability. By diverting waste from landfills, waterways, and natural habitats, these projects contribute to the reduction of pollution and habitat degradation. For example, chemical recycling of plastic waste prevents the incineration or uncontrolled disposal of plastics, thereby reducing marine and terrestrial pollution. The creation of value for plastic waste can incentivize collection and recycling activities, which may otherwise be economically unviable. Similarly, the conversion of agricultural waste to fuels and chemicals reduces the prevalence of open burning, a practice associated with air quality deterioration and transboundary haze events in the ASEAN region.

Circular economy strategies are also associated with reductions in greenhouse gas (GHG) emissions. The utilization of waste-based feedstocks typically results in a lower carbon footprint compared to the use of virgin fossil resources or open burning of residues. Global analyses estimate that circular economy measures could reduce GHG emissions by up to 22.8 billion tons, representing approximately a 39% reduction from business-as-usual projections by 20501. In the context of Southeast Asia, the production of fuels from biowaste or industrial waste gas can displace fossil fuel consumption and lower net CO_2 emissions. Technologies such as the LanzaTech waste-gas-to-fuel process exemplify the reuse of carbon that would otherwise be emitted, with the resulting fuels contributing to a closed carbon cycle [20]. Additionally, many circular processes are less energy-intensive than conventional production pathways; for instance, producing plastics from recycled monomers may require up to 50% less energy than from naphtha, and biofuels derived from waste oils generally entail lower energy inputs than those from dedicated crops.

Resource conservation and biodiversity protection are further benefits. Sourcing chemicals and fuels from waste streams alleviates pressure on natural resource extraction, thereby reducing the need for new oil wells or agricultural expansion. In Southeast Asia, the use of palm oil waste for fuel production can moderate the demand for new plantations, while recycling plastics reduces reliance on petroleum extraction. These effects collectively support forest conservation, water resource management, and the prevention of environmental contamination from landfill leachate [18].

6.2 Economic Benefits and Opportunities

The transition from waste to value-added products through circular economy initiatives presents significant economic opportunities. By creating value from previously underutilized materials, these initiatives can establish new revenue streams and industries, contributing to economic growth and employment generation. Global estimates frequently cite the circular economy as a multi-trillion-dollar opportunity1. For ASEAN member states, increased circularity can reduce expenditures on raw material imports and stimulate domestic innovation and competitiveness. Companies adopting circular practices may realize efficiency gains and enhanced brand reputation, particularly as consumer demand for sustainable products increases.

Case studies from the region illustrate these dynamics. The advanced recycling plant in Johor, Malaysia, is expected to create high-technology manufacturing and skilled employment opportunities. The cellulosic ethanol project in Thailand has established a new segment within the biofuel industry, supporting rural employment in feedstock supply and facility operations. Palm waste valorization initiatives in Malaysia and Indonesia generate value-added processing roles in addition to traditional agricultural employment.

Circular economy practices can also enhance energy security by increasing the domestic production of biofuels and biogas, thereby reducing reliance on imported fossil fuels. This is particularly relevant for countries such as Thailand and the Philippines, which import significant volumes of oil. Furthermore, municipalities may benefit from reduced waste management costs and potential revenue from the sale of waste-derived materials. The development of circular systems can also improve supply chain resilience by enabling local sourcing of feedstocks and reducing vulnerability to global commodity price fluctuations.

Inclusive economic benefits are possible through the integration of informal waste sector participants and smallholder farmers into formal circular economy projects. For example, programs that compensate farmers for agricultural residues or incentivize waste collection can contribute to poverty alleviation and community development, while simultaneously improving environmental outcomes.

6.3 The Role of Cross-Sector Collaboration

The successful implementation of circular economy initiatives frequently depends on collaboration among academia, industry, government, and civil society. Academic institutions contribute research and technological innovation, as demonstrated by the development of enzyme technologies for bagasse conversion and new catalysts for palm oil mill effluent valorization. Industry partners provide the capacity for scaling and commercialization, while governments establish enabling policy frameworks, incentives, and regulatory support. Civil society organizations play a role in ensuring social inclusion and raising public awareness.

Collaboration often extends internationally, as evidenced by partnerships between Japanese agencies and Thai institutions, or the deployment of European technologies in Malaysian projects. Such cross-border cooperation facilitates knowledge transfer and accelerates the adoption of best practices. Industry-wide collaboration is also essential, particularly in the chemical sector, where value chain integration is necessary to achieve circularity1. Effective implementation of Extended Producer Responsibility (EPR) schemes, for example, requires alignment among brands, local governments, waste collectors, and recyclers.

7. Recommendations for Accelerating Circular Economy Adoption

The transition toward a circular economy in the fuels and chemicals sectors represents a significant paradigm shift in resource management and environmental responsibility. While global momentum and technological advancements have been observed, particularly in Southeast Asia, the widespread implementation of circular practices remains in its early stages. Achieving circularity at scale will require coordinated, sustained efforts across academia, industry, policy-makers, and civil society.

7.1 Recommendations for Academia
7.1.1 Research and innovation for local solutions

Academic research should prioritize the development of technologies tailored to local waste streams and conditions. This includes the adaptation of processes to the specific composition of municipal and agricultural waste in Southeast Asia, such as high-moisture palm empty fruit bunches. Research areas of importance include the design of efficient catalysts for plastic depolymerization, the development of fermentation organisms capable of processing mixed or contaminated substrates, and the creation of modular recycling units suitable for deployment in remote areas. Additionally, strategies for the valorization of low-value or mixed wastes, such as municipal solid waste or multi-layer packaging, should be advanced to expand waste-to-resource pathways.

7.1.2 Interdisciplinary systems approach

Universities are encouraged to foster interdisciplinary collaboration among engineers, environmental scientists, economists, and social scientists to address the multifaceted challenges of the circular economy. Systems-level research, including life-cycle analysis and supply chain modeling, can inform the optimization of value chains and policy interventions. Establishing dedicated centers for circular economy studies may facilitate such interdisciplinary efforts.

7.1.3 Pilot projects and demonstration

Academic institutions can bridge laboratory research and industrial adoption by leading pilot and demonstration projects. Collaboration with industry and government partners is recommended to secure funding and operational support for demonstration facilities, such as small-scale pyrolysis units or pilot biogas plants. These projects serve as testbeds for technology validation and provide essential data for industry investment decisions.

7.1.4 Education and skill development

Incorporating circular economy concepts into engineering and science curricula is essential to prepare future professionals. Specialized courses on topics such as green chemistry, biorefinery engineering, waste management technology, and circular economy business models are recommended [18]. The five business models of circular economy are illustrated in Figure 3. Extension programs and professional training for industry practitioners and public-sector officials can further support the adoption of circular practices.

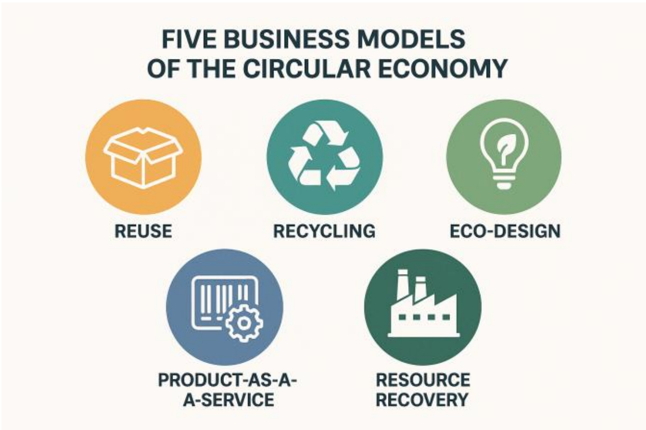

Fig. 3. Five business models of circular economy

7.2 Recommendations for Industry
7.2.1 Integration of circularity into core strategy

Companies in the chemicals and fuels sectors should embed circular economy principles into their business models and research and development priorities. This includes setting targets for recycled or bio-based feedstock usage, investing in recycling and waste conversion facilities, and redesigning products for recyclability. Strategic reviews may identify opportunities for new business units focused on secondary materials sourcing and product responsibility.

7.2.2 Collaboration and value chain partnerships

Active collaboration across the value chain is essential to ensure the supply and demand for circular products. Public-private partnerships, collaborations with startups and technology providers, and cross-industry initiatives can facilitate the development and scaling of circular solutions. Joint ventures and industrial symbiosis approaches can optimize the use of by-products across sectors.

7.2.3 Consumer engagement and product responsibility

Industry should engage consumers through campaigns promoting recycling, proper waste segregation, and the acceptance of recycled-content products. Initiatives such as take-back programs, smart labeling, and rewards for returning used containers can support extended producer responsibility (EPR) compliance and enhance consumer participation in circular systems.
7.2.4 Transparency and reporting

Companies are encouraged to measure and publicly report circular economy metrics, including waste reduction, recycling rates, secondary material usage, and product lifecycle impacts. Adopting recognized standards and frameworks can facilitate benchmarking and accountability, and may enhance access to sustainable finance.

4. Conclusions

The transition from a linear to a circular economy in the fuels and chemicals sectors is complex and requires coordinated action across multiple stakeholders. Academia plays a critical role in innovation and talent development, while industry is responsible for investment and implementation. Effective communication, cooperation, and long-term commitment are essential to realize the environmental and economic benefits of circularity. The adoption and scaling of circular economy practices will contribute to reduced emissions, resource conservation, and the development of sustainable value chains in Southeast Asia and beyond. The establishment of innovation hubs and testbeds, where academia and industry collaborate on research and development, is recommended. These platforms can support the scaling of promising technologies and facilitate knowledge exchange. Joint advocacy for evidence-based policy and the replication of successful case studies across the region are also important for accelerating circular economy adoption.

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References

[1] Bruce Maughon. "The Chemical Industry’s Overlooked Role Ushering in the Low-Carbon Economy." *World Economic Forum*, March 29, (2023).
[2] Matthew Lee. "The State of Plastic Circularity in Asia. " *Lux Research*, July 29, (2024).
[3] World Economic Forum. "Making the $4.5 Trillion Circular Economy Opportunity a Reality." November 14, (2019).
[4] UNCRD. "State of Plastics Waste in Asia and the Pacific." UNCRD 10th 3R Forum, December (2020).
[5] World Economic Forum. "The World Needs a Circular Economy. Let’s Make It Happen." June 3, (2025).
[6] Bioenergy International. "Shell Bets on Pyrolysis and Unveils Energy and Chemicals Park Singapore Plans." November 4, 2022.
[7] Nazrin Suratman. "Shell Building New Pyrolysis Oil Upgrader Unit in Singapore." *ICIS*, November 23, 2021
[8] Shell Eastern Petroleum. "Shell Singapore invests in waste plastic-to-chemicals." Biobased Diesel Daily, Nov. 24, 2021.
[9] Argus Media. "Shell to build pyrolysis oil upgrader in Singapore." Nov. 23, (2021).
[10] Rulianah, Sri, Shabrina Adani Putri, Prayitno Prayitno, Listiyana Candra Dewi, and Ahmad Zaky Aldillah. "Production of bioethanol from sugarcane bagasse using cellulase enzyme." In *E3S Web of Conferences*, vol. 605, p. 01008. EDP Sciences, (2025). https://doi.org/10.1051/e3sconf/202560501008
[11] New Energy and Industrial Technology Development Organization (NEDO). "Construction of a Demonstration Plant Producing Raw Materials for Ethanol from Sugarcane Bagasse Has Been Completed in Thailand." July 6, 2018
[12] Pacific Northwest National Laboratory (PNNL). "PNNL and LanzaTech Receive Award for Ethanol-Based Jet Fuel." May 18, 2020.
[13] Alice Smith and Benjamin Jones. "Sustainable Aviation Fuels from Waste Oils: Current Status and Future Prospects." *Fuel* 300 (April 2021): 121045.
[14] Kai Chen, Yuan Zhao, and Hao Li. "Digital Technologies Enabling Circular Economy: Blockchain, AI, and IoT Applications." *Sustainability* 13, no. 4 (February 2021): 1987. https://doi.org/10.3390/su13041987.
[15] PwC Japan and PwC Sustainability. "Japan and ASEAN Collaborate to Create the Future of a Circular Economy – Executive Sustainability Forum Report, " 2023.
[16] PETRONAS Chemicals Group and Plastic Energy. "PCG to Construct Asia’s Largest Advanced Chemical Recycling Plant-Press Release." October 9, 2023.
[17] Mohammad Rahman, Siti Abdullah, and Nurul Ahmad. "Palm Oil Mill Effluent Valorization via Bioconversion to Bio-

Jet Fuel: A Review." *Journal of Cleaner Production* 320 (May 2022): 128789. https://doi.org/10.1016/j.jclepro.2021.128789

[18] Rizzarelli, Paola, Alessio Zuliani, and Narendra Reddy. "Chemistry and the circular economy." *Frontiers in chemistry* 11 (2023): 1350994. https://doi.org/10.3389/fchem.2023.1350994

[19] Bowker, Michael, Serena DeBeer, Nicholas F. Dummer, Graham J. Hutchings, Matthias Scheffler, Ferdi Schüth, Stuart H. Taylor, and Harun Tüysüz. "Advancing critical chemical processes for a sustainable future: challenges for industry and the Max Planck–Cardiff centre on the fundamentals of heterogeneous catalysis (FUNCAT)." *Angewandte Chemie* 134, no. 50 (2022): e202209016. https://doi.org/10.1002/ange.202209016

[20] Dagle, Robert A., Vanessa Dagle, and Johnny Saavedra Lopez. " Improved Value of the Gasoline and Fuel Oil Co-Product Fractions Generated by the PNNL/LanzaTech Alcohol-to-Jet Process." No. PNNL-30831; CRADA-394. Pacific Northwest National Laboratory (PNNL), Richland, WA (United States); LanzaTech, Inc., Skokie, IL (United States), 2020. https://doi.org/10.2172/1959780

[21] Vietnam Briefing. "Vietnam Introduces National Action Plan for Circular Economy by 2035." March 17, 2025.

[22] Yeoh, Min Li, and Chun Sheng Goh. "Hydrotreated vegetable oil production from palm oil mill effluents: Status, opportunities and challenges." *Biofuels, Bioproducts and Biorefining* 16, no. 5 (2022): 1153-1158. https://doi.org/10.1002/bbb.2365